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PATTERNED GROUND AS AN ARID LAND PHENOMENON

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The *Dictionary of Geologic Terms* defines patterned ground as "... symmetrical surface patterns such as polygons, stripes, and circles, characteristic of, but not confined to soils subject to intensive frost action."[1] Despite this definition, researchers have been reluctant to use the term when describing features which occur outside areas of intensive frost action, especially when such features are observed in warm, dry environments. Most often, arid land patterned ground features are held to be relicts of some earlier climatic episode,[2] or are said to mimic or simulate features characteristic of cold climates.[3] Frequent use of the term "gilgai" to denote surface patterns observed in arid environments underscores this reluctance to consider periglacial and arid land surface patterns as related phenomena. Distinctions drawn between periglacial and arid land features tend to obfuscate the many similarities which exist between them, making more difficult the task of understanding the genesis of desert patterned ground.

The present work examines patterned ground features observed at several locations in California's Mojave

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Desert in order to demonstrate that patterned ground is a phenomenon of arid as well as periglacial environments. Further, an attempt is made to provide an explanatory description of a process which could account for the formation of the patterns observed.

Historical Perspective on Arid Land Patterned Ground

In recent years, most research into the genesis of desert surface features has occurred outside the United States. This was not the case for the period extending from the late 1950's to the early 1970's. During that time, many individuals and groups conducted studies in the Mojave Desert of California and Nevada. Hunt and Washburn, for example, collaborated on an intensive study of patterned ground features in and around Death Valley.[4] That study focused on the role of salt solution and precipitation coupled with temperature changes above freezing. Despite their demonstration of a close correlation between the presence of salt at the surface and the occurrence of patterned ground features, Hunt and Washburn were unable to establish whether the patterns formed due to salt, or the salt accumulated because of the patterns. In a later study, the same authors assumed that salt was, indeed, a major factor in the genesis of the patterns observed.[5] While salt features may, indeed, include surface patterns which could be classed as patterned ground (Figure 1), those features represent only one type of desert surface pattern. Patterns under consideration here are marked by the presence of pebbles at the surface, not salt frets.

Other descriptions of desert surface features have tended to give patterned ground features only slight notice. Cooke, in his study of desert pavements, did note that patterned ground features do, on occasion, interrupt

Figure 1. Polygonal surface pattern produced by salt fretting. Death Valley, California, May, 1972.

pavements.[6] Though this observation was quickly followed by a comment concerning frost action, Cooke did present a compelling argument for the upward movement of coarse particles through a clay matrix as an important factor in the formation of desert pavements. He did not, however, extend his argument to include the patterned ground features he observed. Similar conclusions regarding desert pavements were reached by Springer[7]; but, again, patterned ground was not a focus of the study and, therefore, not commented upon, even though such features are often observed in pavements (Figure 2). Springer did establish that desert soils do exhibit an active layer, which he called the "vesicular layer," through which transport could take place. This active layer, subject to a wet/dry cycle, is similar to the active layer of periglacial regions, subject to a freeze/thaw cycle.

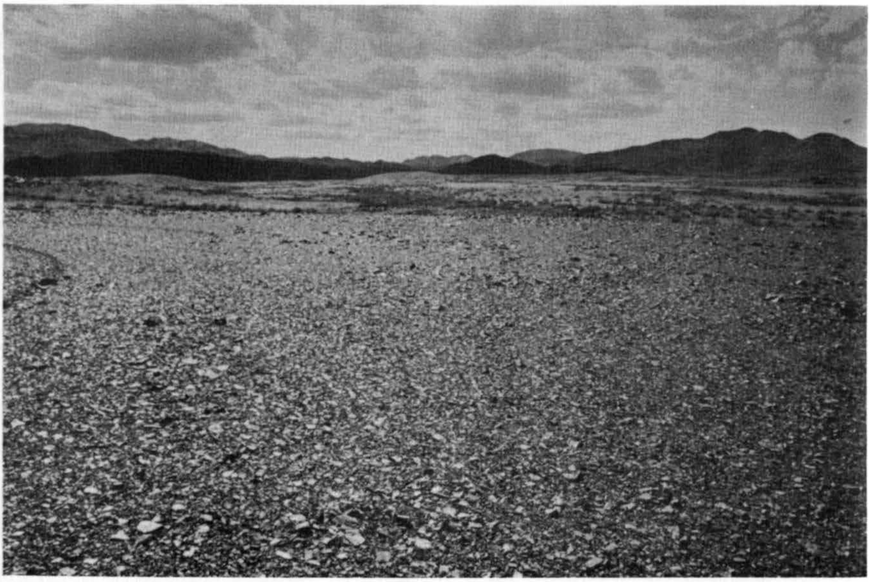


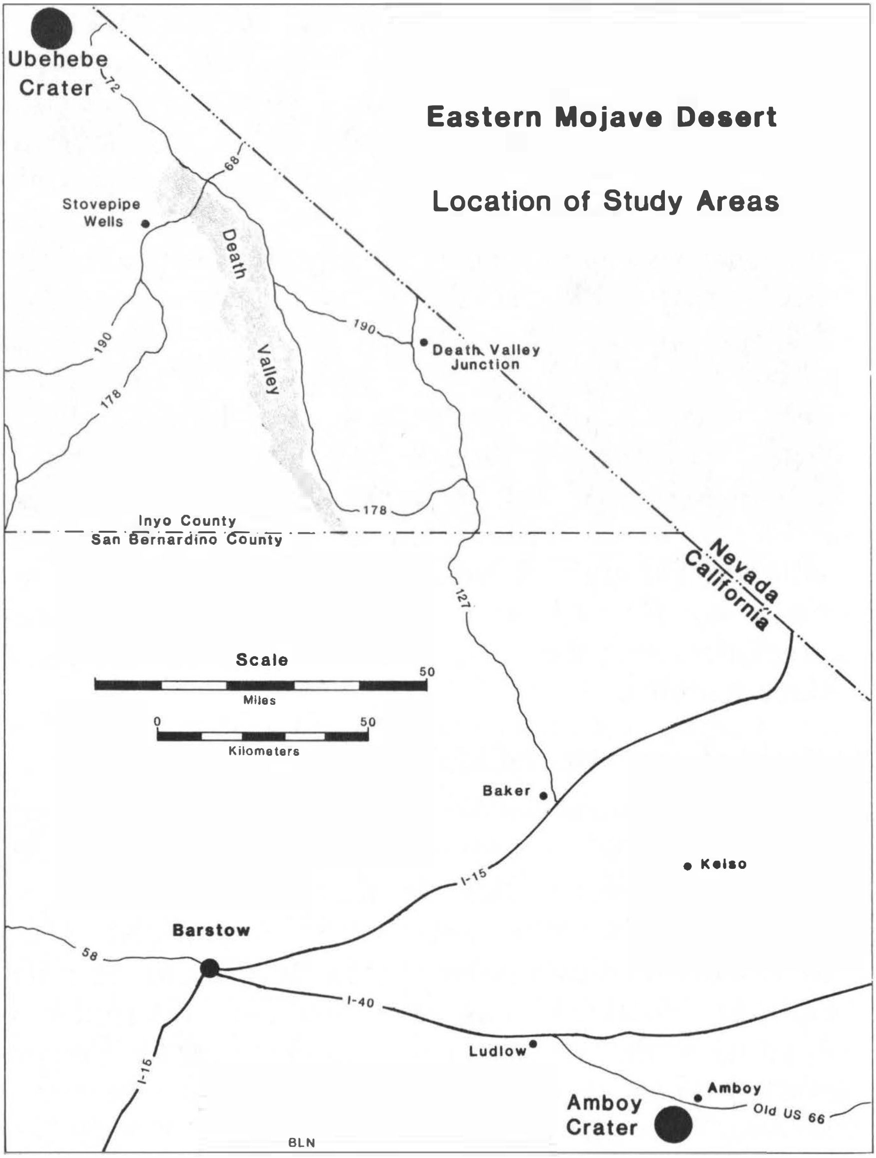
Figure 2. Typical desert pavement, these are often interrupted by patterned ground features.

From the late 1950's to the present, many individuals were concerned with patterned ground or gilgai features found at various locations outside the deserts of California and Nevada. Harris undertook the classification of gilgaied soils in Iraq.[8] White and Bonestell examined similar features in North Dakota.[9] Tedrow studied frost action in periglacial soils and drew some comparisons between the features he observed and similar forms found in arid environments,[10] but he did not provide an explanation for the presence of such forms in deserts. Considerable research has been done in Australia where the term gilgai originated, and much work continues to be done there. Recently polygonal patterns have been observed in New Guinea, on slopes subject to an intense wet/dry cycle.[11] This latter study stresses the importance of phase changes in water during the cycle, but does not explain the mechanisms which produce surface patterns.

The historical record suggests that simple observation and description of desert patterned ground features are insufficient to provide an explanation of the genesis of this desert phenomenon. To understand its formation more fully, desert patterned ground must be viewed in a broader context than that of traditional geomorphology and pedology, although these remain basic to understanding of all surface features. As will be discussed later, soils which are subject to an intense wet/dry cycle may behave as viscous fluids during the wet phase. Meteorology, a science which deals with the atmosphere and the behavior of fluids, can contribute to the understanding of desert surface features. Using techniques developed through cloud formation experiments described by Brunt,[12] it is possible to gain a broader appreciation and, therefore, understanding of desert soil surface features.

Patterned Ground in the Mojave Desert

Patterned ground features are well-known throughout the Mojave Desert. The variety of surface forms described in previous studies runs the gamut from frets and stones to stripes and pavement. Studies already cited provide detailed description of those forms and their distribution. Features considered here are restricted to polygonal forms which occur in association with recent basalts and their weathering products. Basalts are found at several locations in the eastern portion of the Mojave Desert. For the present study, detailed observations were carried out in two areas over a period extending from 1971 to 1983 (Map 1).


Eastern Mojave Desert
Location of Study Areas
Ubehebe Crater
72
68
Stovepipe Wells
Death Valley
190
178
Death Valley Junction
Inyo County
San Bernardino County
Nevada
California
127
Scale
50
Miles
0
50
Kilometers
Baker
Kelso
I-15
Barstow
58
I-40
Ludlow
I-15
Amboy
Amboy Crater
Old US 66
BLN

Map 1.

In both areas, recent cinder cones represent the dominant local landform. Amboy Crater near Amboy, California, dominates the southern study area (Figure 3), while Ubehebe Crater, near Death Valley, dominates the northern. Both craters are of fairly recent origin. It is assumed that basaltic materials found in their vicinity date from the era of most recent activity. Also, because local drainage tends to be internal, it has been assumed that both coarse and fine materials found at or near the surface are products of local basalt weathering.

Weathering products include blocks of vesicular basalt, pebble-sized fragments, and clay-sized particles.[13] Consistent with basalt weathering, the clays are predominantly montmorillonites.[14] As indicated earlier, salts play an important role in local weathering, as do other chemical and mechanical processes.

Figure 3. Amboy Crater viewed from the west, May, 1972. (G. O. Tapper photo)

The primary study area centers on Amboy Crater. The field area was first visited in May, 1971. At that time, the general distribution of polygons was noted, and slope characteristics were measured. The area was revisited annually until 1978, and field studies were undertaken in May of each year. This allowed the annual precipitation cycle to run its course. Since this portion of the desert exhibits a winter concentration of rainfall, May represents the end of the local wet season. Only minor changes were noted between annual visits in the size and distribution of polygons. Within the crater, polygons which formed near the margins of small playas (Figure 4) showed significant cumulative change. Here, the polygons actually grew during the course of the study.

In 1971, the mean diameter of selected polygons was 15.5 cm.; by 1978 the mean was 17.5 cm. This indicates

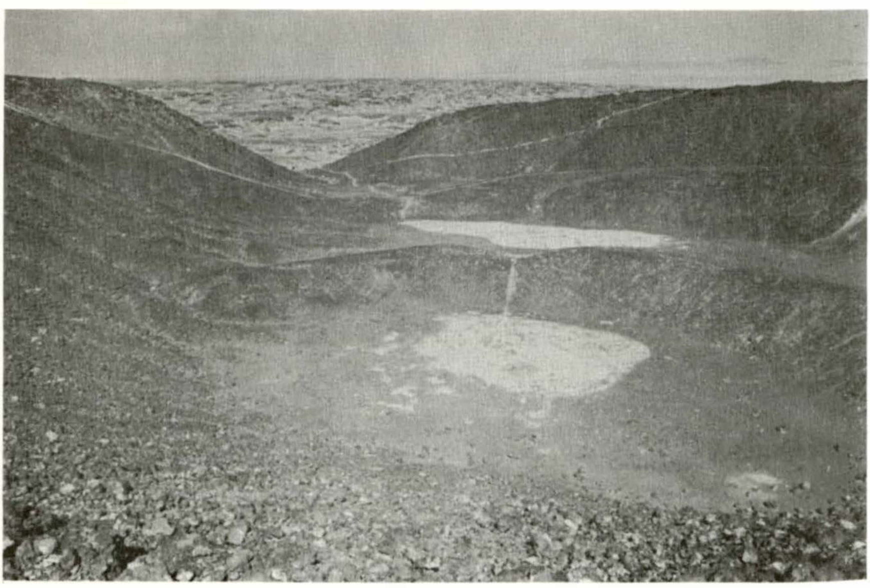


Figure 4. Small playas within Amboy Crater, an indication of internal drainage, May, 1971.

that polygon formation is an ongoing process, and that the features observed are not relict. In order to substantiate this, randomly selected polygons were excavated (Figure 5). The excavations showed that surface boundaries extended through the active layer, leading to the conclusion that the patterns observed represent a surface expression of cellular divisions within the active layer. Each polygon represents a clay lens extending through the active layer. As will be discussed later, the diameter of the polygon is an indication of the depth of the active layer.

Once excavation was complete, and measurements were taken, lenses were refilled. Coarse materials were placed within one of the lenses at a depth of 5 cm. In an attempt to determine if upward transport would take place, more pebble-sized material was placed in the lens

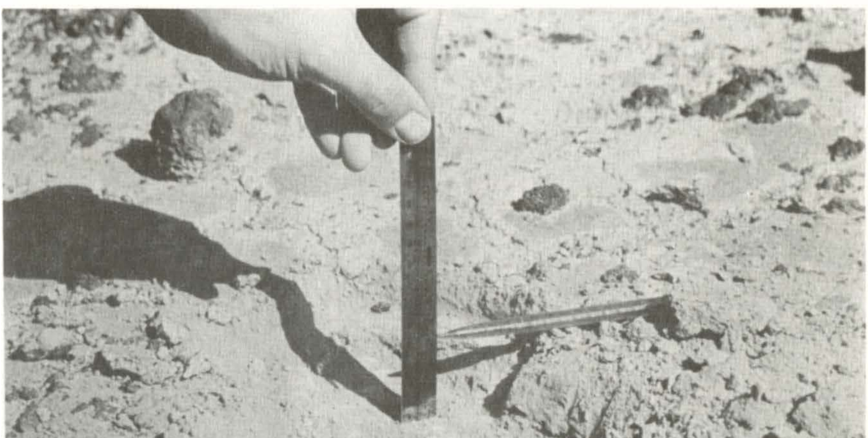


Figure 5. Excavation of a clay lens reveals the cellular nature of the active layer. Amboy Crater, May, 1978.

than had been removed. It was assumed that the presence of more coarse materials than in neighboring polygons would cause the polygon, if it reformed, to be distinct. It was further assumed that failure of the polygon to exhibit a different surface expression would indicate that material transport occurred laterally within the active layer, and that the cellular structure of the layer was impermanent. By May of 1983, the polygon had reformed. Its boundaries did show a higher concentration of pebble-sized particles than its neighbors (Figure 6), indicating that the basic structure of the active layer is indeed cellular, and that coarse materials were transported upward. However, at this point, the mechanism for transport was not determined.

Between 1978 and 1983, the Amboy Crater sites were not visited. Instead, it was decided to concentrate on

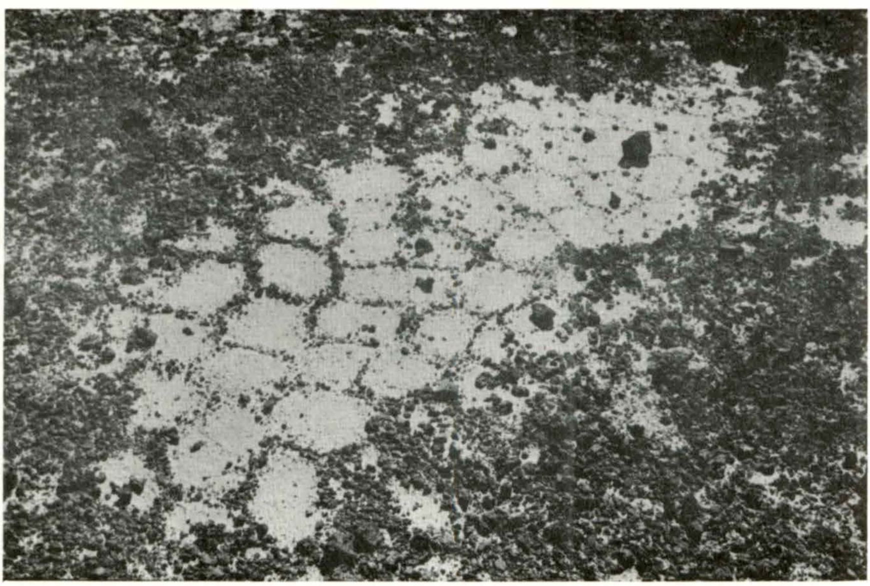


Figure 6. Hexagons reformed after five years. This is the same area which was excavated in 1978. Amboy Crater, May, 1978.

another area in hope of determining whether the polygons observed represented a merely local phenomenon, or whether generalities could be drawn which would permit the identification of areas where similar features could be found.

Comparisons of topographic and geologic maps at a scale of 1:62,500 indicated that the area in and around Ubehebe Crater exhibited surface conditions much like those found at Amboy. The areas were also similar climatically, with Ubehebe receiving slightly less precipitation. In an initial on-site inspection, polygons similar to those found at Amboy were observed, and their distribution and morphology were noted. Excavation of randomly selected polygons revealed that diameter/depth relationships fell within the range of those observed at Amboy (Table 1). Additional excavations made during the 1981 and 1982 field seasons confirmed that diameter/depth relationships remained constant. Demon-

Table 1.
Dimensions of Polygons as Determined by Excavation

	Depth of Active Layer	Diameter of Polygon	Location
1.	57.3 cm	17.8 cm	Amboy Crater
2.	46.2 cm	15.1 cm	120m. N. of Amboy Crater
3.	47.4 cm	15.4 cm	120m. N. of Amboy Crater
4.	50.0 cm	16.0 cm	75m. E. of Amboy Crater
5.	49.9 cm	16.1 cm	75m. E. of Amboy Crater
6.	52.5 cm	17.2 cm	Ubehebe Crater
7.	56.0 cm	17.2 cm	30m. W. of Ubehebe Crater
8.	55.8 cm	18.3 cm	1km N. of Amboy Crater
Mean	51.8 cm	16.6 cm	

strable similarities between the two areas of study led to the assumption that a general description of patterned ground associated with recent basalts and their weathering products would suffice for both areas. From this general description, conclusions might be drawn regarding the genesis of desert polygons.

Patterned ground features observed at both Amboy and Ubehebe tend to develop most rapidly and are most easily observed near the margins of small playas within and near the respective craters. It appears that evaporation and the energy transfers resulting from that process, combined with the swelling of clays, provides the force which moves coarse materials through the active layer. Polygon boundaries are marked on the surface by pebble-sized, rounded fragments of vesicular basalt. Because of their vesicular nature, the pebbles are relatively low density and are easily transported through the denser clay layer. The clay layer itself is composed of expandable, hydrophilic clays. It is assumed that the expandable nature of the clays plays an important role in starting the transportation process. Salts are important as an element in the weathering process, but probably play only a minor role in polygon formation.

The diameter of each polygon is dependent upon several variables, not all of which are presently understood. Polygons measured during the course of this study fell into the range of 15-18 cm. Although the basic shape of the polygons is hexagonal, distortions due to slope were noted. Polygons distorted by slope exhibited an elongation parallel to the axis of the slope (Figure 7). An earlier study indicated that at about 18 degrees of slope, the polygonal form would be replaced by stone stripes.[15] This is consistent with observations made during the course of this study.

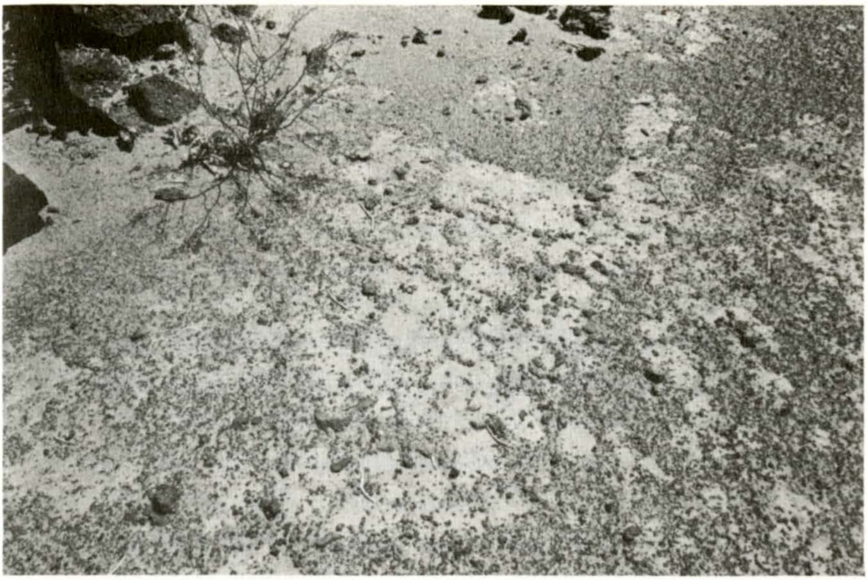


Figure 7. Distortion of polygons due to slope. These forms developed on a slope of approximately 15 degrees. Near Ubehebe Crater, May, 1979.

Excavation indicates that the depth of the active layer plays a controlling role in determining polygon diameter. The ratio between clay and pebbles present is also important. If there is a paucity of coarse material, the surface most likely will appear as a simple series of mud cracks. If there is a super abundance of pebble-sized material, the surface may simulate a desert pavement. The active layer itself is defined as that portion of the soil mantle which is subject to the wet/dry cycle. Its upper limit is marked by the soil/atmosphere interface, and its lower limit by the presence of an impermeable layer, such as bed rock or hardpan. This is the vesicular layer as described by Springer,[16] and it is analogous to the active layer which experiences a freeze/thaw cycle in periglacial environments as described by Davies.[17] From the several excavations made, it appears that the diameter of a surface polygon is equal to approximately one-third the depth of the active layer. Distortions due to slope made it most difficult to determine whether the same relationship existed for elongated polygons.

Similarities between periglacial and arid land patterned ground abound. Not only do surface patterns appear similar, but subsurface patterns also mimic each other.[18] The major difference between the forms studied here and those in periglacial regions is scale. Periglacial polygons tend to be much larger than those studied here. Other relationships, however, appear constant. Since upward transport is a major factor in the formation of periglacial patterns, it would follow that a similar action would be involved in the formation of so similar a form as arid land patterned ground. This conclusion is consistent with the findings of several researchers concerned with arid land surface features, though debate still exists over a precise mechanism of transport.

Jessup, for example, concluded that soil turbulence produced the patterns,[19] although he did not account for the cause of the turbulence. Ollier speculated that vertical swelling and shrinking of expandable clays caused transport and produced the familiar patterns.[20] This matter of determining the precise mechanism of transport has caused great consternation and produced several lively debates in the literature. In all probability, elements of both processes are involved.

If the active layer is assumed to go through a variety of stages in the course of an intense wet/dry cycle, it may be considered a highly viscous fluid when saturated.[21] While in this fluid stage, energy is transported through the active layer, from the bottom to the top of the layer by convection. The clay lens then may be viewed as a simple convection cell. Because the active layer does experience a fluid phase, and that fluid is divided into cells, it is possible to use principles of cellular convection, borrowed from the field of meteorology, in an attempt to enhance our understanding of desert surface polygons.

Cellular Convection and Patterned Ground

While in its fluid phase, the active layer is unstable. Also, clay particles within the layer swell. This condition of instability is ephemeral. As dessication begins, instability decreases and the clays shrink. A basic tenet of meteorology holds that when instability of a fluid initially at rest begins to break down, the fluid divides into a series of polygonal cells.[22] The process in question was first described by Benard,[23] and the polygonal forms which result from decreasing instability are commonly called "Benard cells." Motion within a Benard cell consists of upward movement at the center, outward at the surface, downward at the edges, and inward at the bottom as shown in Figure 8.

In arid lands, rapid evaporation at the surface and the subsequent movement of moisture and energy upward through the active layer produces instability. Coarse materials are transported upward through the clay. Once at the surface, these coarse materials are no longer surrounded by the clay matrix. Pebbles and other coarse materials can be pushed outward, but the downward motion at the edges of the cell do not affect them. When dessication is complete, stability is established, and the familiar polygonal arrangements are left at the surface. As in periglacial areas, the active layer experiences alternating periods of stability and instability as it goes through its solid and fluid or liquid phases. Energy is exchanged at the surface in both the arid and periglacial cases.

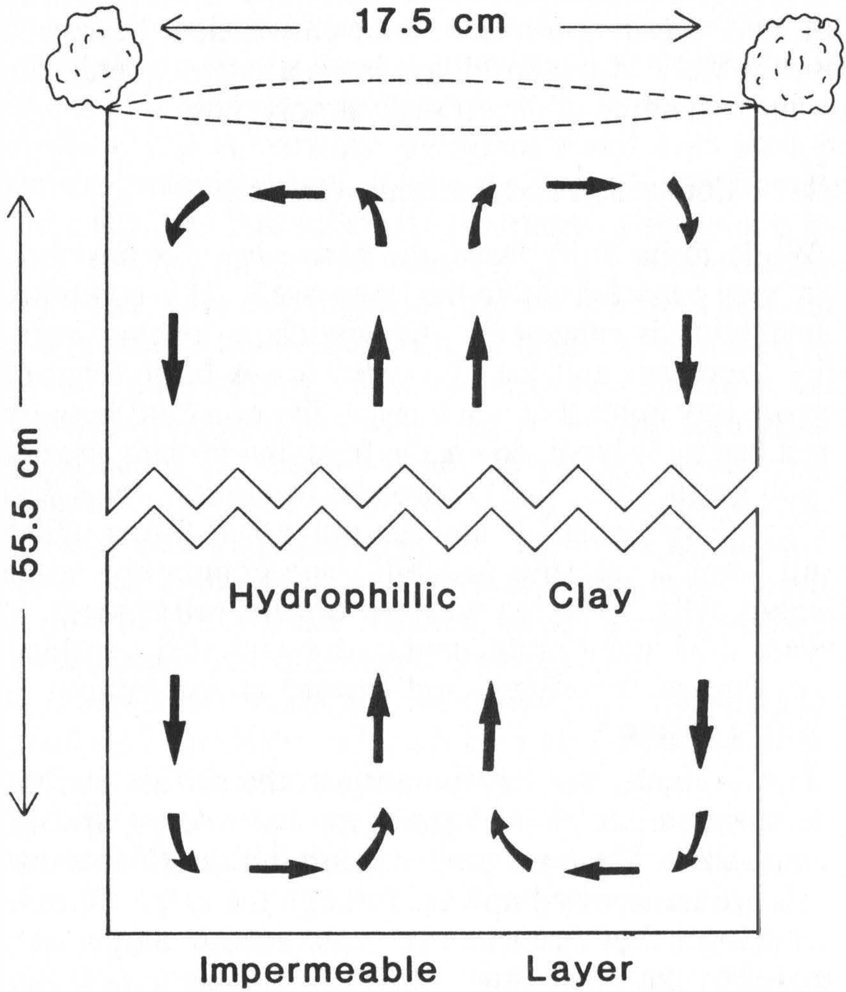


Figure 8. Idealized cross section of a clay lens. Arrows indicate direc-rtion of convectional movement in a Benard cell.

Not all soils which experience an intense wet/dry cycle, or freeze/thaw for that matter, exhibit polygonal surface patterns. Two factors could account for this: insufficient density gradients through the active layer, or the absence of coarse materials. With respect to the first of these, Lord Rayleigh theorized that ". . . no motion will occur in a 'statically' unstable liquid, unless:

$$\frac{p^1 - p^0}{p} > \frac{27\pi^4 kv}{4gh^3}$$

where p^1 equals the density at the top of the layer, p^0 the density at the bottom of the layer, and p the the mean density within the fluid; k is the coefficient of thermometric conductivity; v the kinematic coefficient of viscosity; and h the depth of the layer."[24]

Rayleigh's theorem suggests that the shallower the layer, the greater the difference in density required to produce motion and, therefore, Benard cells; and those cells will become smaller as depth decreases. Benard demonstrated that for a circular cell the ratio of its depth and diameter would be 3.285,[25] a figure close to that observed in the field.

As mentioned earlier, the amount of coarse material available also affects the formation of patterned ground. A lack of coarse materials leaves dessication cracks rather than stone polygons at the surface. If there is no limit to the amount of coarse material available for transport, a stone pavement will result. This latter helps explain why patterned ground features may interrupt desert pavements, and also allows for the assumption that desert pavements and arid land patterned ground share a similar genesis.

Conclusions

It is clear that many processes are involved in the formation of arid land patterned ground. The key to understanding the phenomenon lies in the mechanics of cellular convection. It is necessary to separate weathering processes from the mechanical process which produces patterned ground. Regardless of the role of various weathering agents (for example, salt), polygons will result as long as hydrophilic clays represent the dominant weathering product, and those clays are subject to an intense wet/dry cycle. When coarse materials are present, they will be transported upward to form a polygon, usually a hexagon. The Benard cell provides a reasonable model to describe the motion which occurs during the dessication process. The described motion provides the force which transports coarse materials through the clay matrix to the surface.

Forces and motions generated by the freeze/thaw cycle in periglacial environments are similar to those generated during the arid land wet/dry cycle. In both cases, cooling occurs at the surface of an initially unstable fluid. As instability decreases, the familiar patterns emerge. Similarities which exist between periglacial and arid land patterned ground lead to the conclusion that patterned ground is as much a phenomenon of arid environments as it is of periglacial lands, and that the same process accounts for its formation in both areas.

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NOTES

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17. J. L. Davies, *Landforms of Cold Climates: An Introduction to Systematic Geomorphology*, Vol. 3 (Canberra, 1969).

18. Tedrow, op. cit.

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21. W. W. Emerson, "The Swelling of NA-Montmorillonite Due to Water Absorption," *Australian Journal of Soil Resources*, Vol. 1 (1963).

22. Brunt, op. cit.

23. Ibid.

24. Lord Rayleigh (J. W. Strutt), *Scientific Papers*, Vol. 6 (Cambridge University, 1920), pp. 432-446. [In the equation in question, "g" equals gravity.]

25. H. Benard, "Les Tourbillons dans une nappe liquide," cited in Brunt, op. cit.